Facing the renewable energy storage crisis: Hybrids of concentrating PV with high-T thermal collection

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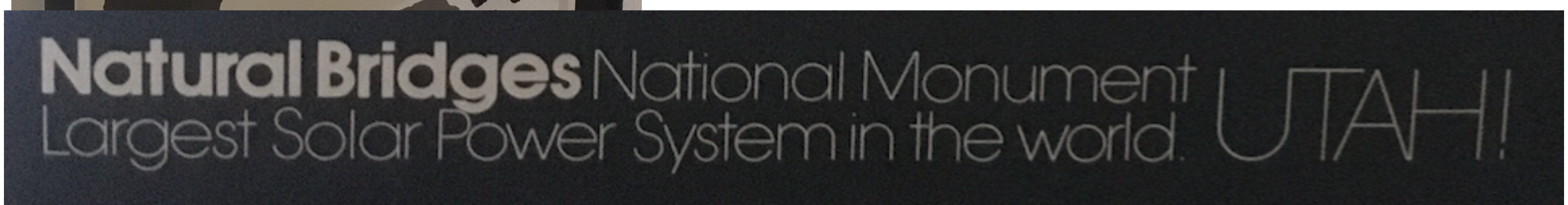
World’s Largest Solar System

Poster I’ve had since 1981!



$37/Watt module price (2016 $)
2 MW of PV installed in world

World's Largest Solar System

1980 – 100 kW in Utah

$37/Watt module price (2016 $)
2 MW of PV installed in world

2016 –China & India claim 850 MW farms

Over 50 plants bigger than 100 MW!

Solar Star, California – 570 MW

Copper Mtn, Nevada– 458 MW

$0.57/Watt modules
277 GW of PV now installed

Supplying 1.4% of world electricity

IEA, Snapshot of Global PV Markets, 2015

Outline

- Impending solar storage crisis
  - Technoeconomics
- Hybrid collector technologies for PV electricity + heat
- Exergy metric for hybrid solar production

The good and the bad of PV solar energy

- Photovoltaic electricity below grid parity in many places
  - $100 billion/year PV business is growing rapidly
  - Generated ~5% of California electricity in 2014
    - Will double by 2020

- Early signs of a storage crisis
  - Germany suffers *oversupply* of solar electrons when the sun is bright
  - California and the U.S. Southwest approaching PV oversupply
  - PV expansion past 10 – 20% electricity penetration is threatened

High solar demand + PV penetration >10% mean > 50% premium value for storage

Branz *et al*, Energy & Env. Science, 2015

- Modeling of California at 33% renewables (coming in 2020!) shows reduced value of additional PV
  - Suggests 60 – 230% premium value for dispatchable solar electricity

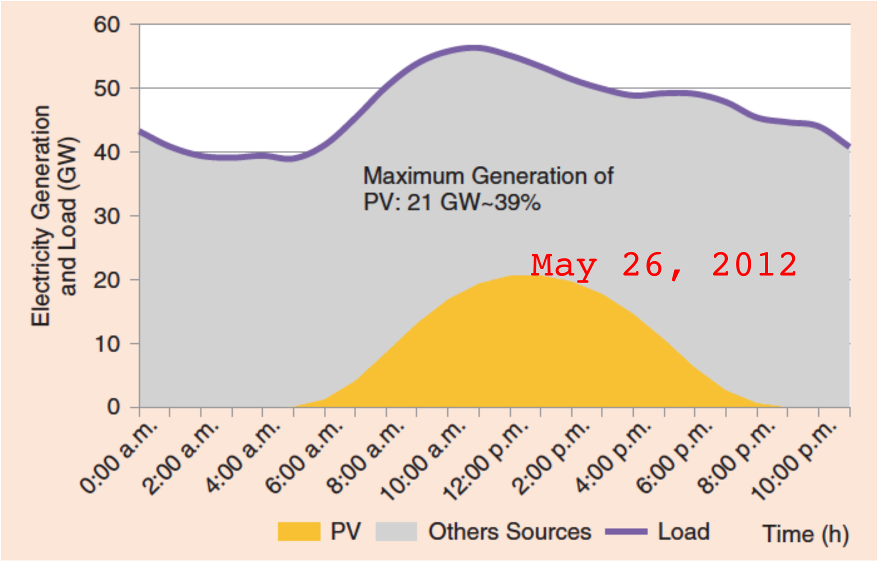
Jorgenson et al, NREL Technical Report, 2014

- Germany is first test case for high penetration

  ~ 6% of annual electricity

  ~ 50% some sunny hours

  - Value of electricity now falls with renewables fraction
  - Negative wholesale electricity price at times of good sun



Von Appen et al., IEEE Power & Energy, 2013

CHANGING WHAT'S POSSIBLE

Thermal storage and conversion to electricity is far less expensive than electricity storage

Branz *et al*, Energy & Env. Science, 2015

Storage	Added cost (¢/kWh_e)	Comments
Pumped hydro	16 - 22	Natural sites scarce
Compressed air in natural caverns	12	Natural sites scarce
Compressed air above ground	> 20	
Batteries today	> 20	
Future battery projections	~ 10	e.g. Li-ion from Tesla Gigafactory
Molten salt thermal storage ~400 C	6	Includes generation*
Molten salt thermal storage ~600 C	3	Includes generation*

Note: Baseline cost of electricity is 10 ¢/kWh_e in most U.S. locations

*Generation includes storage tank, heat exchanger, heat engine and generator

Problem: Expensive to collect heat and make electricity with Concentrating Solar Power (CSP)

Parabolic trough
for 386° C molten salt

Power tower for 600°C molten salt

- CSP electricity expensive at 15 – 20 ¢/kWh_e
  - PV electricity now below 10 ¢/kWh_e in many locations
- Hybrids with PV can lower the $/W of solar heat collection
  - Extract more value from sunlight

Branz *et al*, Energy & Env. Science, 2015

ARPA-E funds 12 hybrid projects with total of $30M from 2014 - 2017

- **F**ull-spectrum **O**ptimized **C**ollection and **U**tilization of **S**unlight

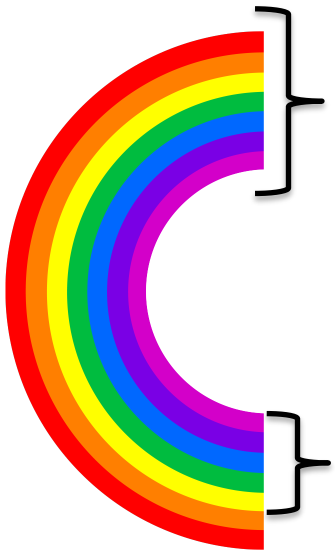
- ARPA-E seeks disruptive new solar technology options
  - Interdisciplinary teams combine thermal and PV solar

- Inexpensive Hybrid Solar Converters
  - Optimized energy collection from each wavelengths in solar spectrum
  - Solar heat collection for energy when the sun doesn't shine

Spectral splitting for dispatchable electricity

Branz *et al*, Energy & Env. Science, 2015

- Splitting exploits strengths of each part of spectrum



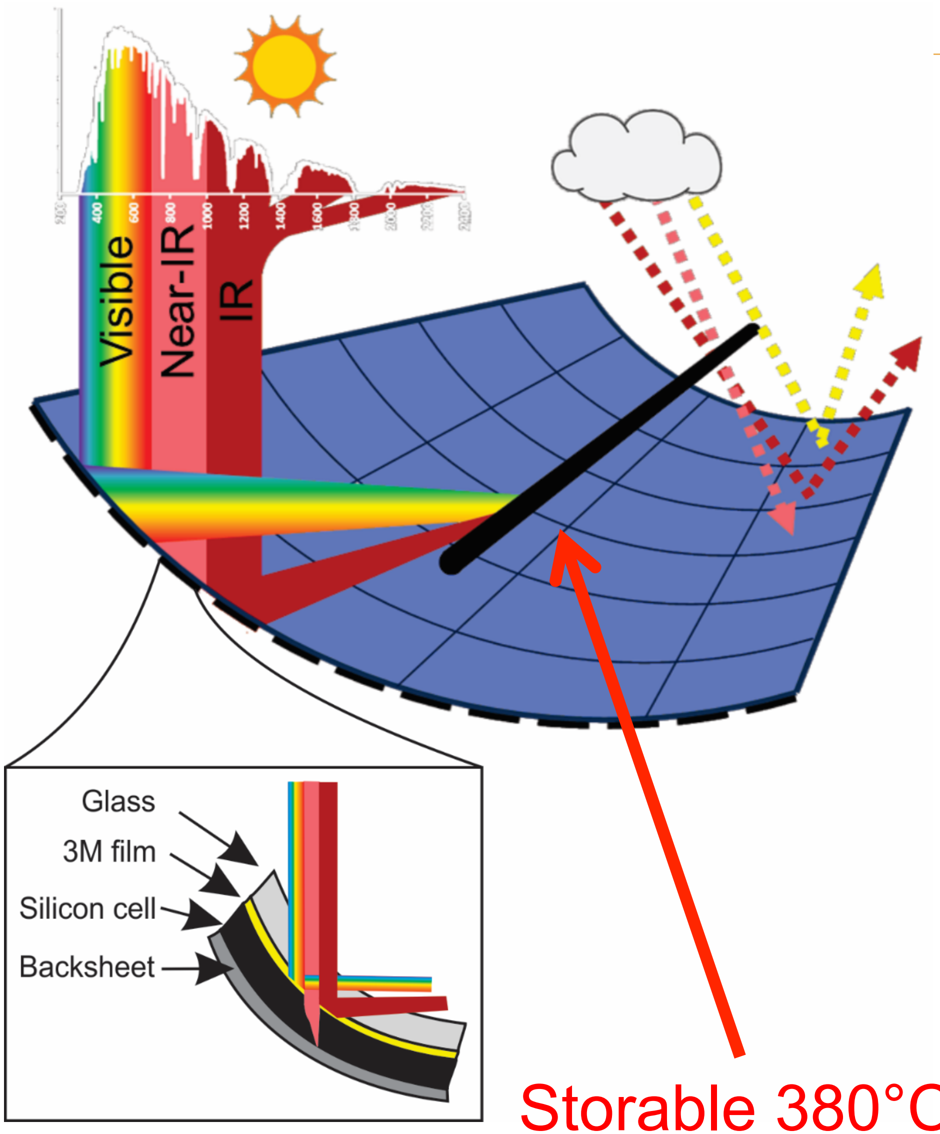
CSP: Solar to heat with 60 to 80%
Through 30-35% heat engine
➔ η < 20% converted to electricity that is dispatachable

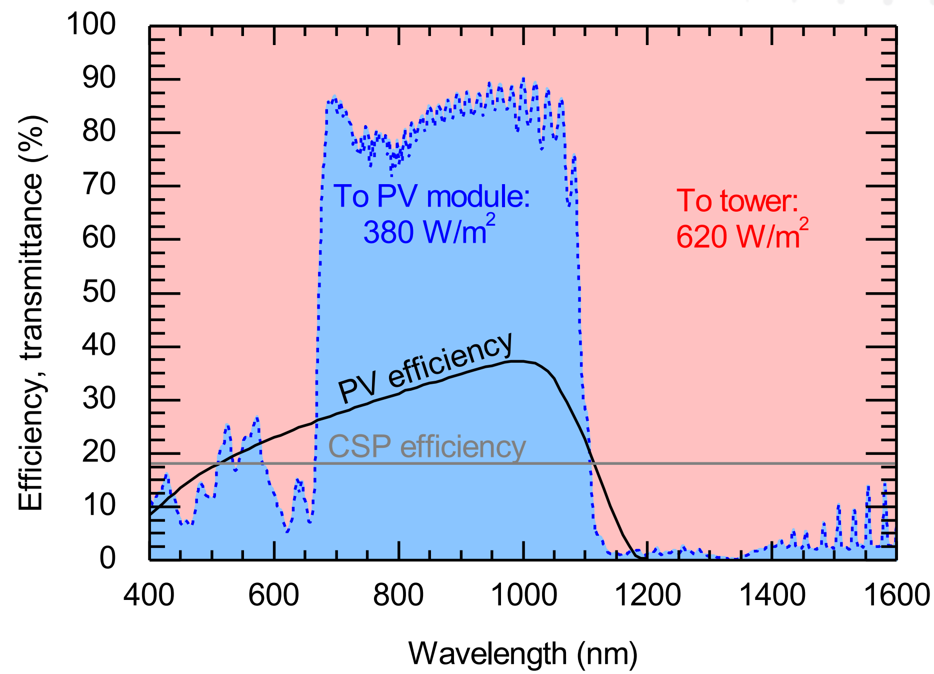
PV: Solar to electricity with 20 – 40%
η ~ 50 to 60% for photons just > PV bandedge (1 – 2 eV bandgaps work best)

- For dispatchability, split spectrum between PV and thermal

PVMirror: Spectrum-splitting trough hybrid

Yu et al., *IEEE JPV* **5**, 1791 (2015)

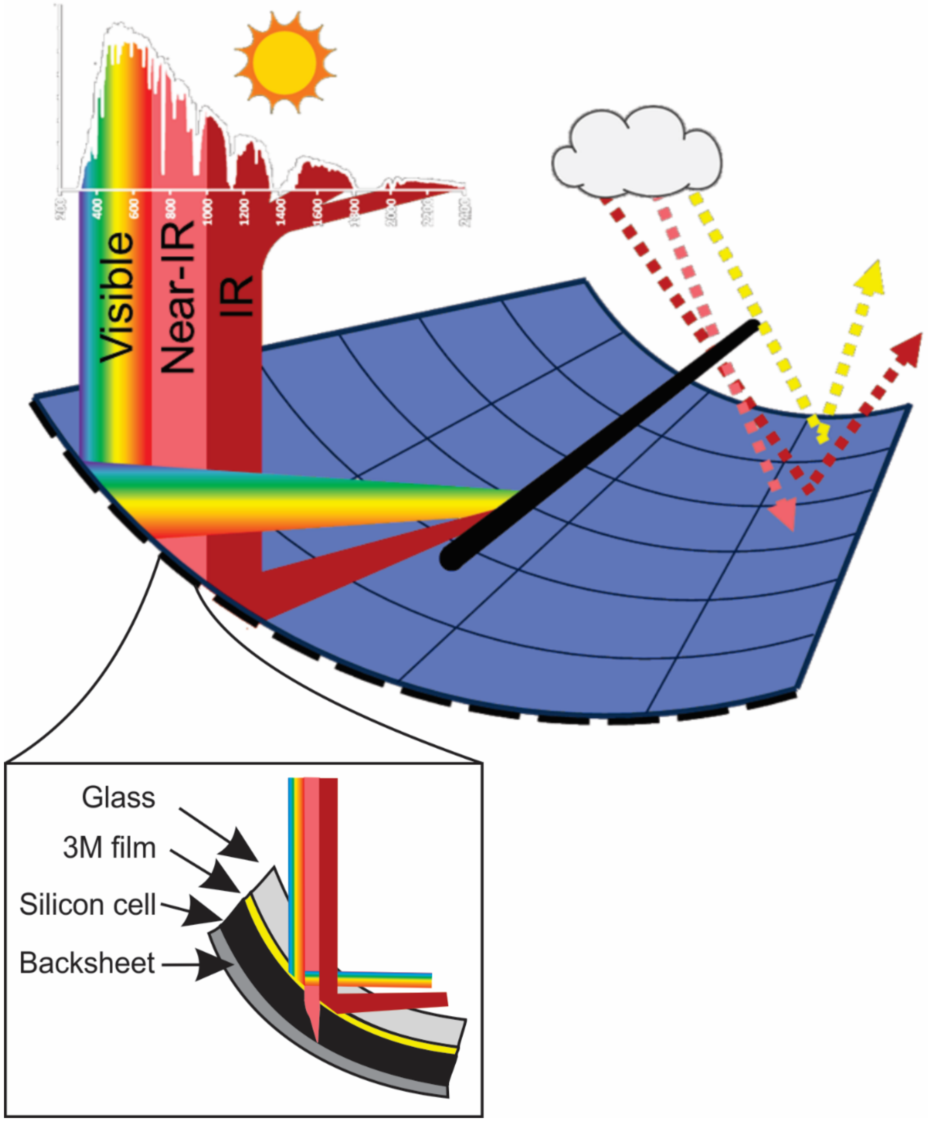




Storable 380°C heat

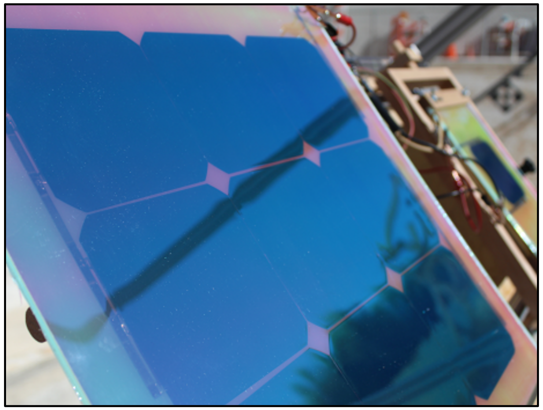
PVMirror: Spectrum-splitting trough hybrid

Yu et al., *IEEE JPV* **5**, 1791 (2015)

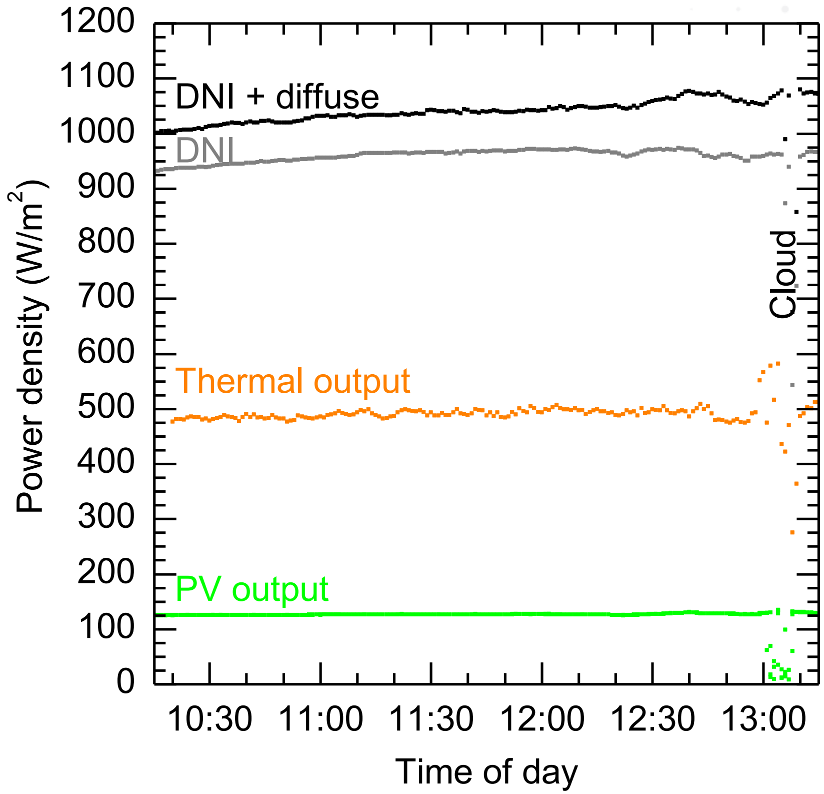


- Collects direct and some diffuse light
  - Full-aperture silicon cells collect NIR light
  - Visible and IR light focused for heat
- 50% higher annual energy than trough CSP with same storage
- Only 10% more $$ than CSP → 20% lower LCOE

PVMirror: Spectrum-splitting trough hybrid



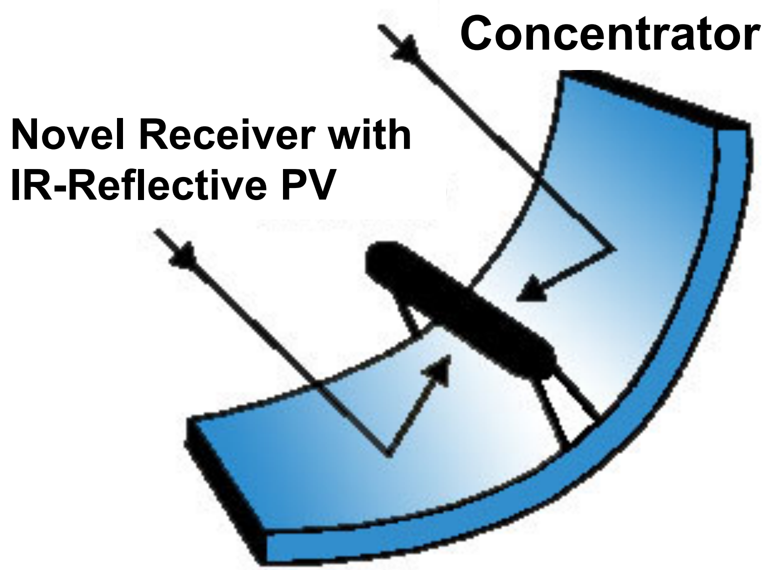
- *12% of the global irradiance is converted to DC electricity by the PV; 50% of the DNI is converted to heat*
- *Corresponds to a 20%-efficient solar – electric power plant*



IR-reflecting PV as Secondary Receiver

R. Winston *et al*, next talk

- Solar receiver for multiple energy streams
  - Electricity from IR-reflecting III-V solar cells
  - Heat at > 500 °C
    - Stored for dispatchable energy

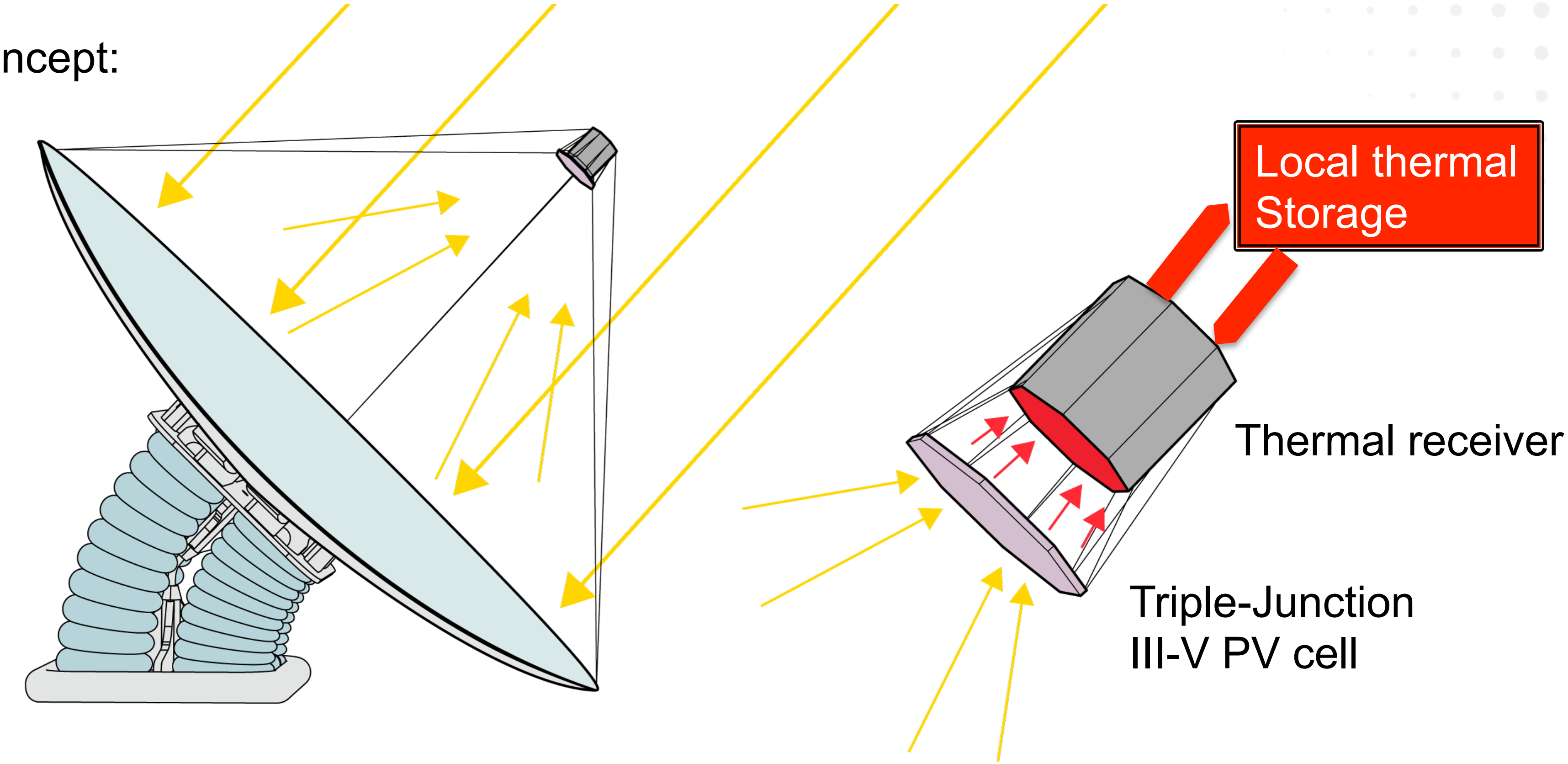


see.murdoch.edu.au/resources/info/Tech/hightemp/

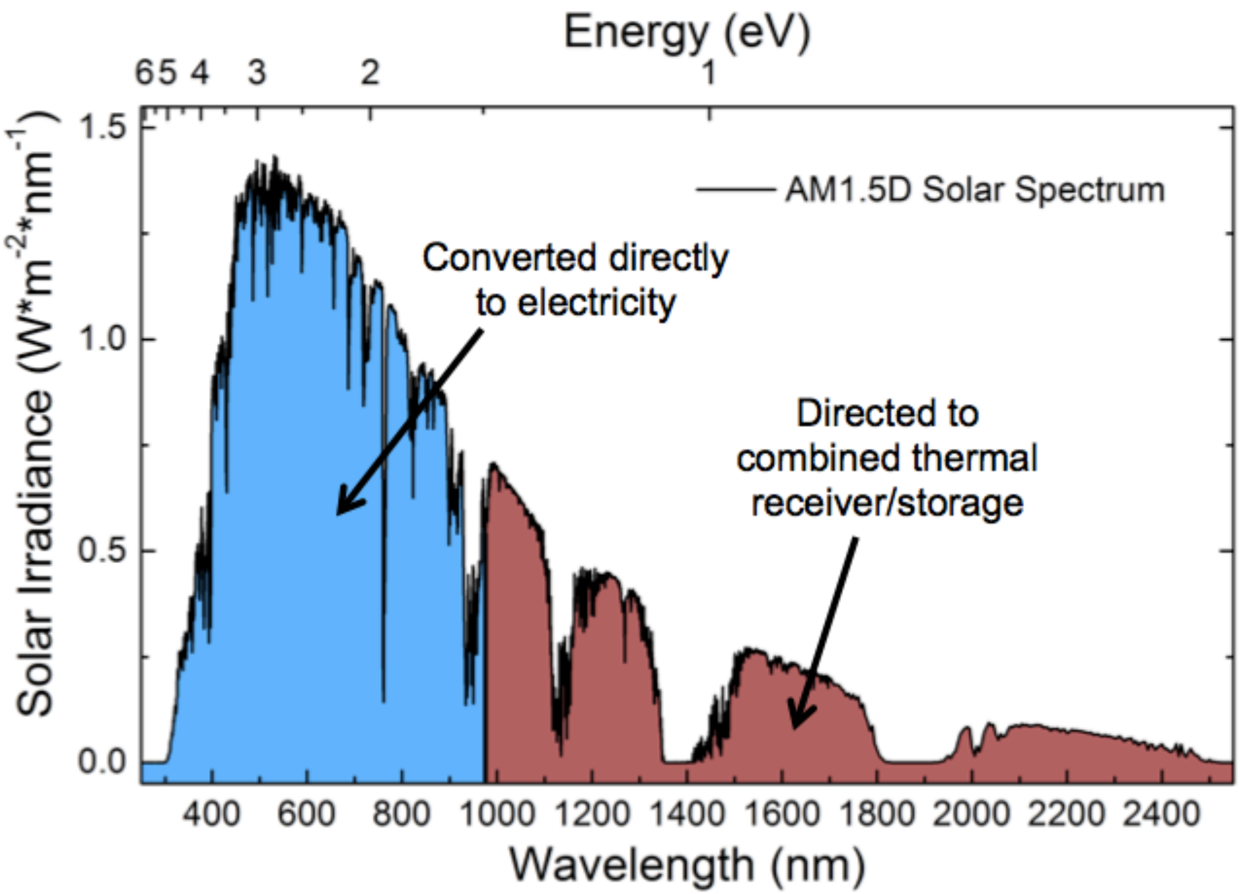
Semi-transparent PV/Thermal on a Dish

Xu, Escarra et al., Solar Energy,2016

Concept:



Full Spectrum Solar Energy Conversion

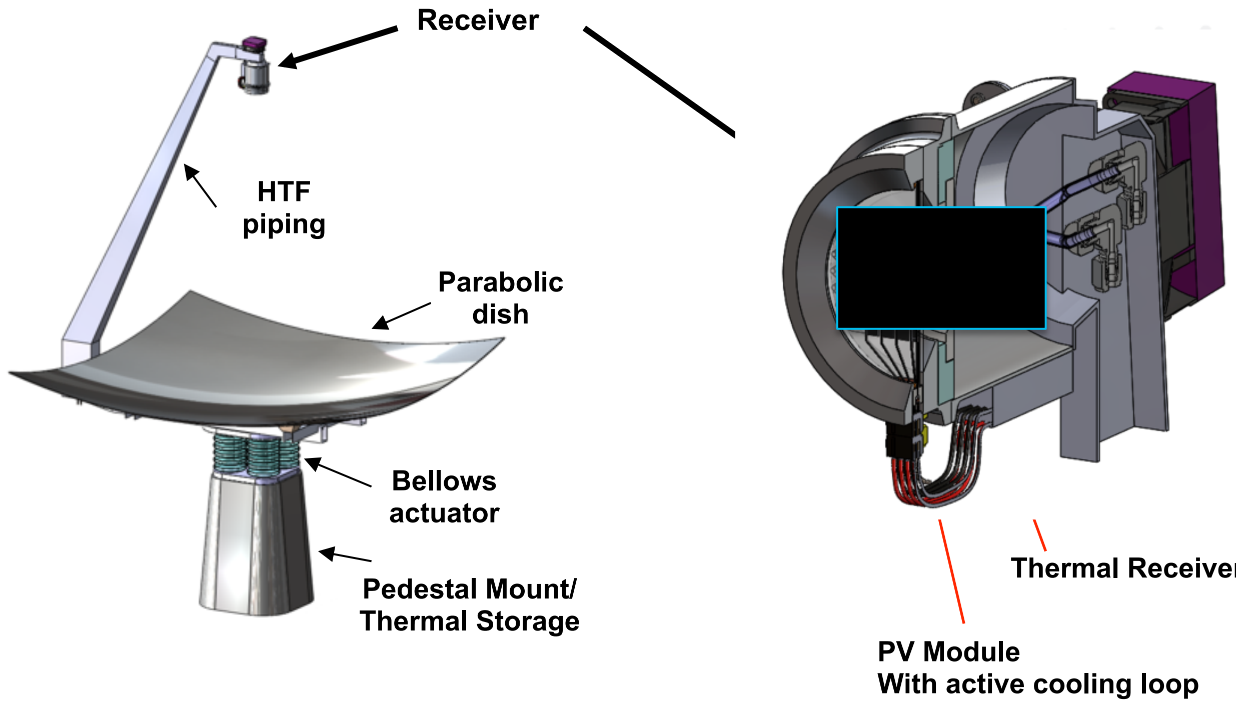


$$\textit{Inband Efficiency} = \frac{\textit{Energy output from CPV}}{\textit{Inband energy to CPV}}$$

Dish for High Optical Efficiency and Modularity

Xu, Escarra et al., Solar Energy, 2016

- 2.7-m^2 dish
  - 2-axis tracking
- 3J III-V PV module
  - 30% efficient at 1-sun
  - 43% for in-band light
  - 42% cell coverage
  - 75% transmission for out-of-band light
- 91% efficient cavity thermal receiver
  - 260 – 560°C thermal storage

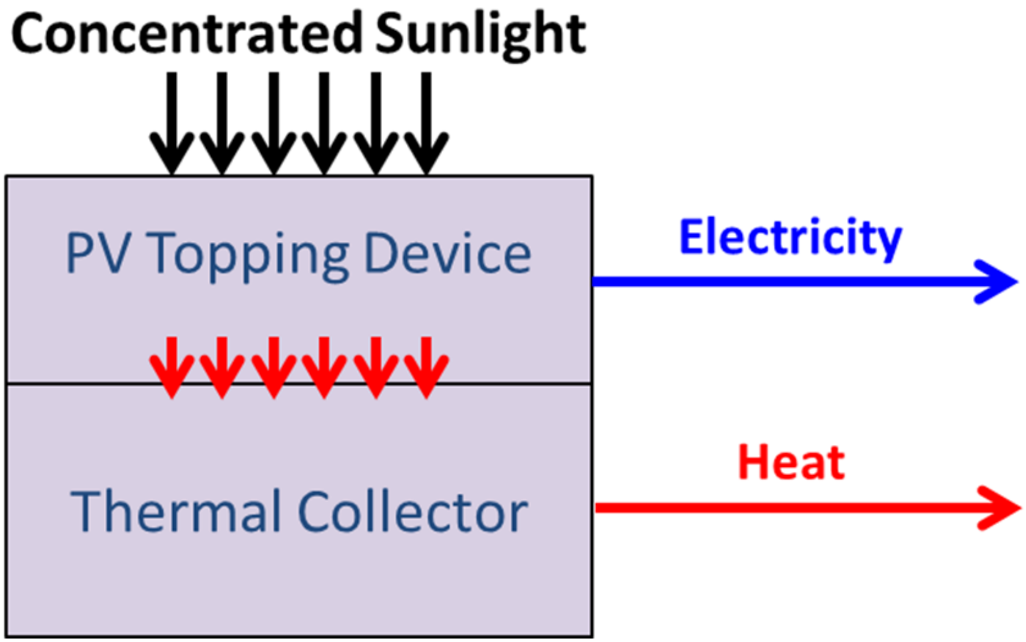


First market may be PV electricity + dispatchable solar industrial process heat

Topping Photovoltaic (PV) cells

Branz *et al*, Energy & Env. Science, 2015

- Develop PV for 400°C use: accept PV efficiency reduction
  - Net system energy efficiency changes little
- Capture PV losses as useful 400°C heat
  - Store heat and generate electricity after sun goes down

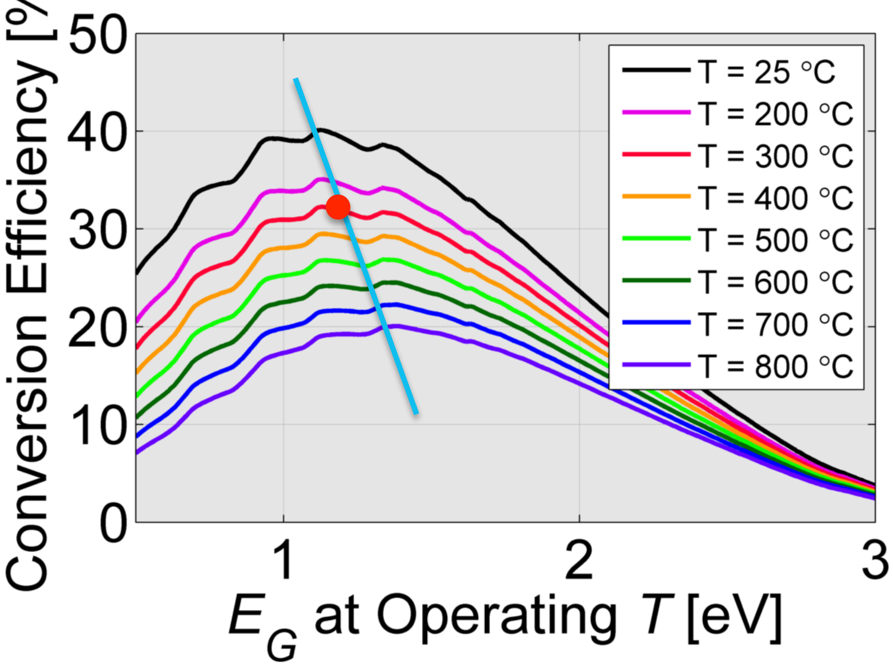


Single-junction PV high T theoretical limits

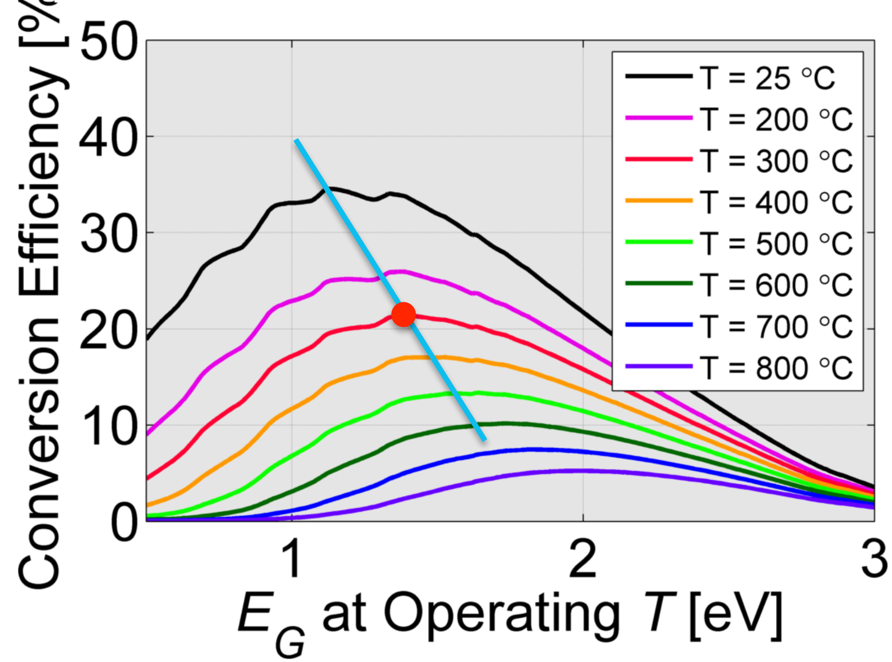
Wilcox & Gray, unpublished
J.R. Wilcox, Purdue PhD thesis, 2013

- Under 500X concentration:

~31% Shockley-Queisser limit at 300°C



~21% Auger & Radiative limit at 300°C

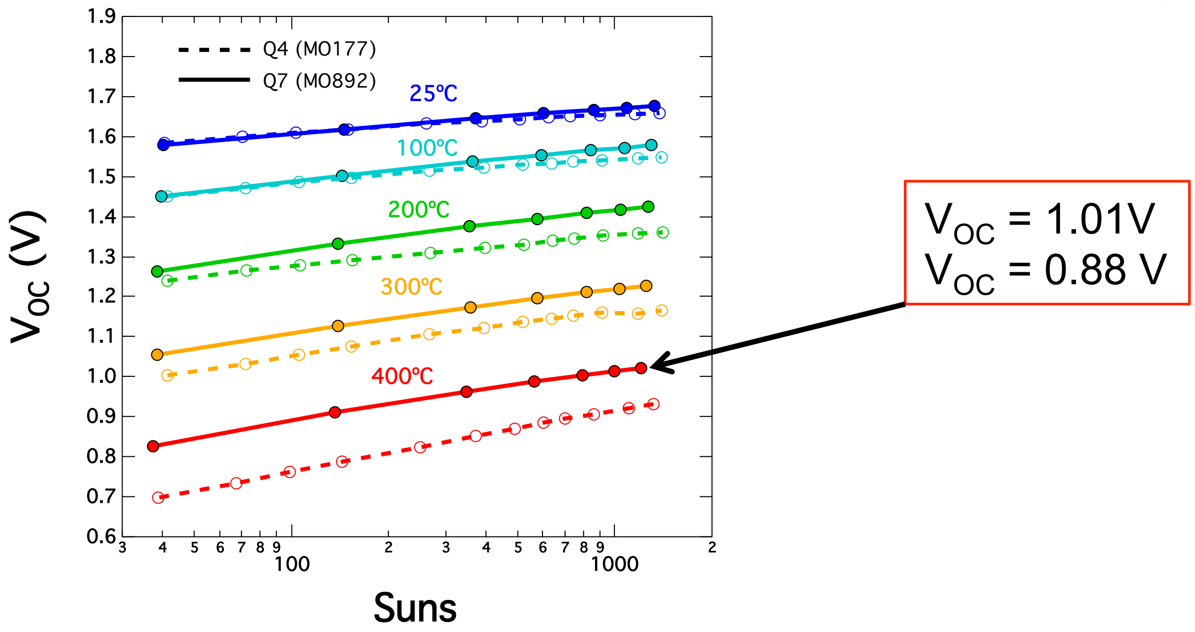


- Higher efficiency achievable with 2 junctions

PV behaves roughly as modeled at 400°C

Minjoo Lee et al., unpublished

- GaInP cell with 1.01 V at 1000x, 400°C

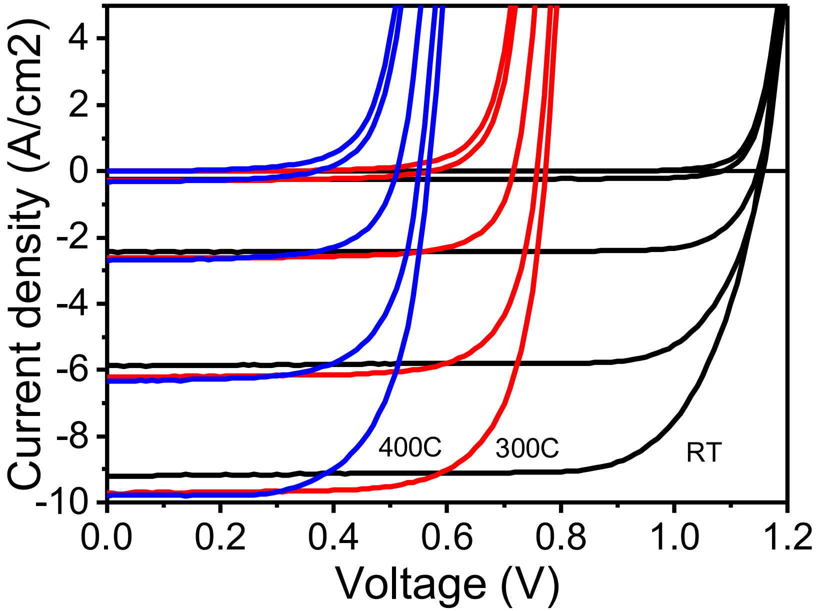


- GaAs bottom cell with 0.74 V at 1000x, 400°C
- Tandem cell should approach the radiative limit

Early durability results suggest 400°C is possible

Minjoo Lee et al, MRS Spring 2016

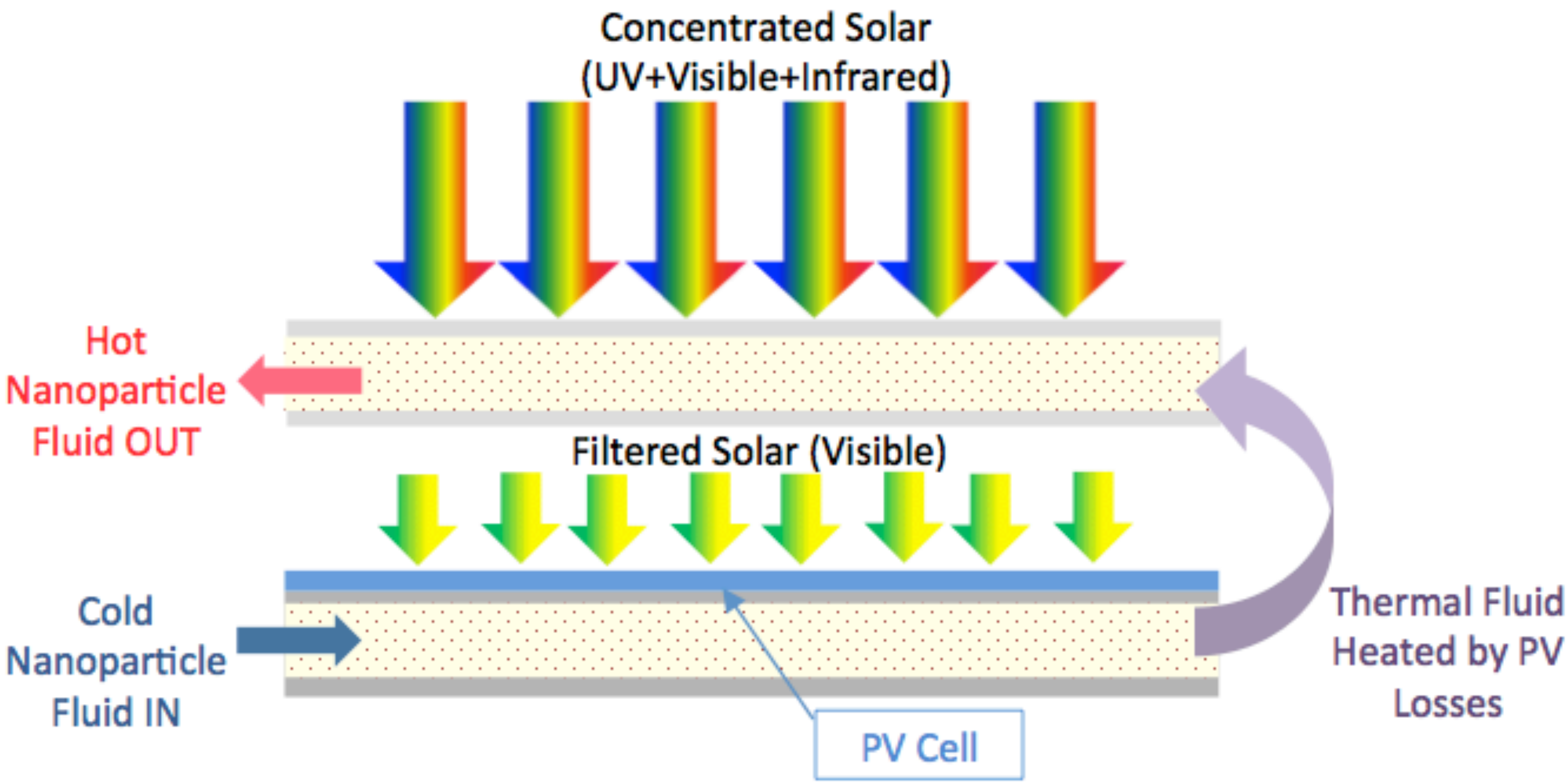
- 2-junction AlGaInP/GaAs in oven for 200 hrs at 400°C measure V_{oc} = 1.54 V at 400°C and 1000x
- 1-junction GaAs with FF~ 0.7 after 200 hrs at 450°C



Liquid Filter with Plasmonic Nanoparticles

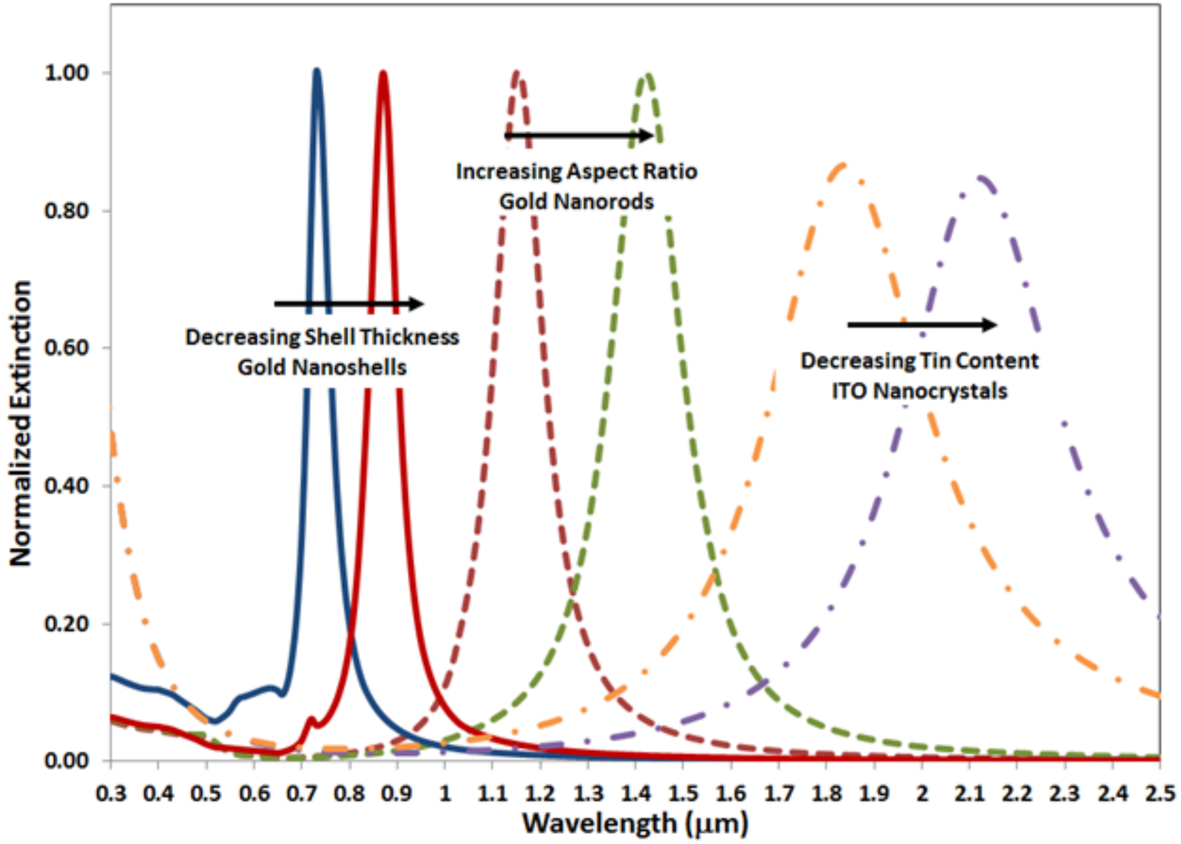
see, Otanicar et al, J. Appl. Phys., 2010
and Brekke et al, J. Solar Energy Eng, 2016

- Combine spectrum splitting with PV-topping



Tunable plasmonic absorption

DeJarnette et al, Sol En Mats & Solar Cells, 2016

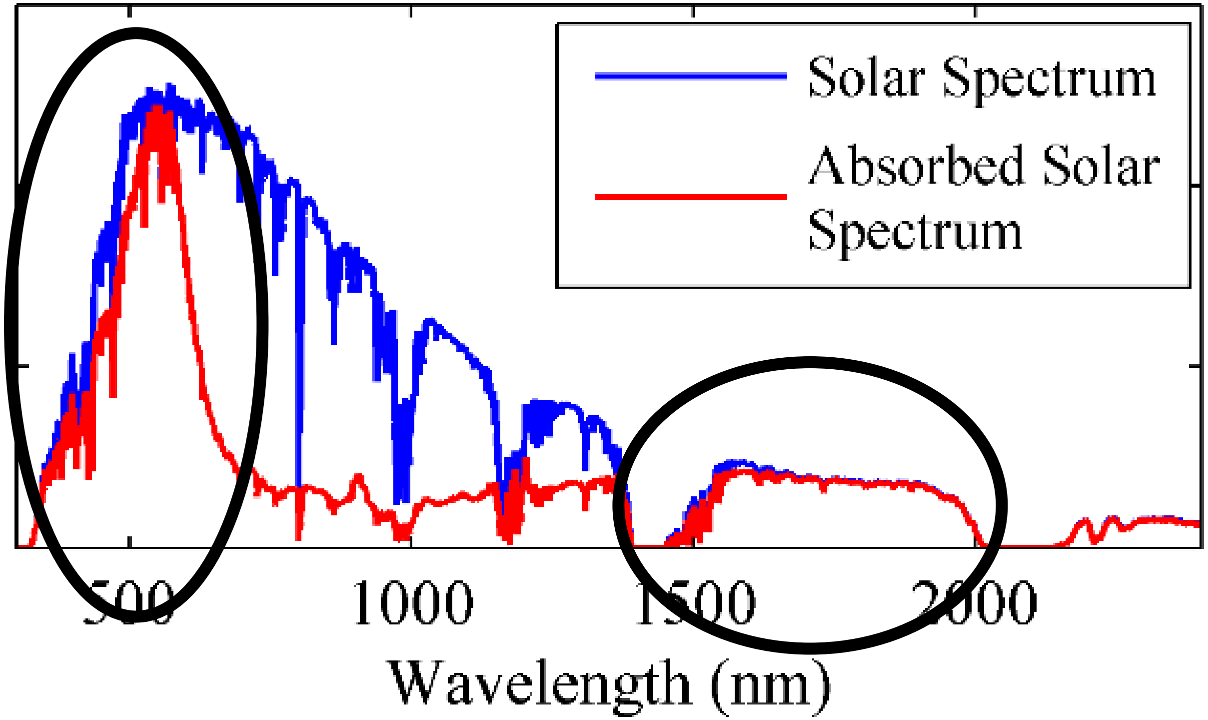


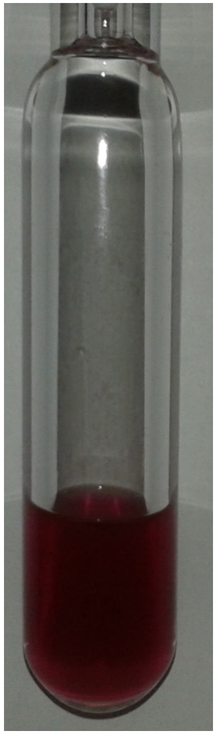
- Challenge: Stable nanoparticles and suspensions at >300°C

Customizable Nanoparticle Mixtures

DeJarnette et al, Sol En Mats & Solar Cells, 2016

Transmit selected band to PV cell





ITO Nanocrystals + Gold Nanospheres

ARPA-E FOCUS set *exergy efficiency* and NOT *energy efficiency* as the goal

Branz *et al*, Energy & Env. Science, 2015

- Hybrid solar systems provide both electricity and heat
  - Need a way to weight their *values*
- Exergy is defined as thermodynamically available energy
  - PV electricity is 100% exergy
  - Solar heat exergy depends on the T_{hot} of that heat energy
  - Carnot fraction could be converted to electricity (in principle)

$$\eta_{Carnot} = (1 - T_{cold}/T_{hot})$$ is typically 50 to 65%

- Real engines actually convert ~2/3 of the exergy to electricity
  - Exergy metric = 50% premium for storable solar energy
  - Maximize $/W of *exergy* for maximum economic value

Conclusions

- Storage of solar electricity needed for high PV penetration
  - Thermal storage/generation less expensive than battery storage
- Hybrid solar energy systems show potential to overcome the solar storage problem
  - PV best for converting photons to electricity in *part* of spectrum
  - High-T PV may allow capture of losses as stored heat (topping)
- ARPA-E FOCUS Program funded 12 interdisciplinary teams to develop hybrid solar converters and 400°C PV cells
  - Seeking maximum *exergy* systems in anticipation of storage needs
  - Scientific publication in full swing
  - First commercialization likely soon --- is the time right?

Thank you

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